Technical-economic performance of fuel cell integration in autonomous hybrid systems

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Article Info

Article history:

Received May 11, 2024
Revised Nov 16, 2024
Accepted Dec 25, 2024

Keywords:

Battery
Diesel generator
Fuel cell
Hybrid system
Photovoltaic

ABSTRACT

Increasing energy demand and greenhouse gas emissions reinforce the importance of renewable resources in energy systems. This study evaluates the technical and economic viability of integrating a fuel cell (FC) in autonomous hybrid systems to supply a community in Algeria, with an average power of 6.91 kW and a daily energy requirement of 165.6 kWh. Four hybrid system configurations were compared using HOMER software: i) photovoltaic (PV) and batteries (BAT), ii) PV, BAT, and diesel generator (DG), iii) PV, BAT, and FC, and iv) PV, BAT, DG, and FC. The PV/BAT/DG/FC system was identified as the optimal configuration, balancing energy efficiency, reducing energy surpluses, reducing reliance on DG, and reducing CO_2 emissions while maintaining competitive energy costs. These results demonstrate that the integration of FC can improve the sustainability and stability of autonomous hybrid energy systems.

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1. INTRODUCTION

Global energy demand, mainly met by fossil fuels, produces environmentally damaging greenhouse gas emissions. To remedy this, developing renewable energies, such as solar photovoltaic (PV), is vital [1]-[3]. Algeria, faced with growing electricity demand, seeks to expand its range of energy sources and reduce its CO_2 emissions by exploiting its enormous potential in renewable energies, particularly solar energy, thanks to its size, wealth, and favorable geographical location [4]. Weather fluctuations pose a major challenge to the continued availability of renewable energy (RE). Hybrid systems, which integrate various energy sources like renewable, conventional fuels, and energy storage systems (ESS), appear to be a solution that improves the reliability of the overall system [5], [6]. Storage systems such as hydrogen fuel cell (FC) respond to the challenge of RE variability, offering increased reliability and an environmentally friendly alternative with expandable storage capacity and extended discharge duration [7]. but, the design and optimization of hybrid systems require careful consideration of complex factors such as the variability of energy supply, component costs, and fluctuating energy demand to achieve optimal results [5]. The literature abounds with studies on optimizing hybrid electricity systems, using software such as HOMER, Hybrid 2, and iHOGA. These tools assess the most effective sizing and operational strategies for various scenarios, examining the technical feasibility, and economic. HOMER is recognized as a commonly utilized software, enabling the design and optimization of hybrid systems, and the estimation of life cycle costs [4], [7] taking into account the costs of

components, load profiles, and natural resources [8]. Among the research conducted in this field, we can identify:

Nassar *et al.* [9] used HOMER to optimize a hybrid renewable energy system (HRES) that include PV, wind and biomass. Vishnupriyan *et al.* [10] optimized a HRES, conducted a feasibility analysis, and determined an optimal solution through an in-depth cost analysis. Chisale *et al.* [11] performed a techno-economic analysis of six hybrid system scenarios to maintain electrical stability and reduce costs in a school, using HOMER and CRITIC-PROMETHEE II methods. The work presented in [12] used HOMER software to technically and economically evaluate three hybrid systems, and a "generator-only" reference system, with the aim of determining the most suitable energy system for an off-grid mining company. A comparative technical-economic study was carried out between a traditional system and an optimized PV-wind system [13]. Research by Kapen *et al.* [14] evaluate two hybrid systems (PV/FC/electrolyzer/biogas, with or without batteries) for energy production in Maroua, Cameroon, using HOMER Pro and considering three consumption levels. The study presented in [15] assesses the viability of integrating RE sources on an isolated island, with the aim of complementing or replacing two existing generators, it also includes both technical and economic analysis and optimization of a hybrid system combining DG and RE. Uwineza *et al.* [16] analyzed the most effective configuration of a hybrid system consisting of PV, BAT, and DG, evaluating various criteria such as system size, cost of energy (COE), unsatisfied electrical load and CO_2 emissions. Aziz *et al.* [17] optimized a hybrid PV/diesel/battery system, comparing a new management strategy to the standard cycle charging (CC) method in HOMER, their approach shows better technical, economic and environmental performances. Al-Badi *et al.* [18] determined a performance comparison of two stand-alone hybrid systems, PV/DG/FC with batteries and PV/DG/FC with a SC storage system, taking into account the energy consumed daily. Abid *et al.* [19] analyzed the integration of PV systems with pumped hydroelectric storage (PHS) and batteries in Burkina Faso. The results indicate that the combination of PV and PHS is optimal for both rural and urban areas, while batteries remain too expensive due to their short lifetime and high costs. Dawood *et al.* [7] developed a simulation, analysis and comparison of three scenarios that use 100% RE with a conventional system with diesel generator (DG). The objective was to find an optimal solution that considers both the energy equilibrium and techno-economic optimization. According to the simulation results, the most economically beneficial scenario is the hybrid ESS with hydrogen batteries.

The results show that hybrid solutions, including combinations of RE sources and storage systems, offer promising prospects in terms of economic and environmental efficiency. Where this paper presents an innovative study on the feasibility, both technical and economic, of integrating FCs into standalone hybrid systems to fulfill the electricity needs of an isolated community load in Annaba, Algeria, as well as modeling all potential scenarios containing various combinations. Although there is a substantial body of research in the literature regarding the techno-economic evaluation of hybrid systems, no previous research has examined this integration in two different hybrid system configurations. Using HOMER software, the study compares different configurations of hybrid systems based on technical, economic, and environmental criteria. After evaluation, the optimal system is selected from four configuration.

This study makes the following contributions: evaluates the integration of FC in hybrid systems to power a secluded community in Annaba, Algeria. improves the technical efficiency of hybrid systems via the integration of FC, and compares the solutions obtained with HOMER softwar, examining various parameters like the share of renewable energies, operating costs, energy surpluses, costs energy, and polluting emissions. This analysis intends to identify the ideal configuration for the integration of the hybrid system at the designated location.

2. METHOD

This study, carried out in Sidi Salem, Annaba, in northeastern Algeria (36°51.6' N, 7°46.8' E), uses 22 years of meteorological data to assess the solar potential of the site, as illustrated in Figures 1 and 2. This study develops four hybrid configurations via HOMER: PV with battery; PV with battery and DG; PV with battery and FC and PV with battery, DG and FC, to supply a community load of 6.9 kW with a daily energy requirement of 165.6 kWh. The highest demand, reaching 23.31 kW, occurs in July, the estimated lifetime of the system is 25 years, with a minimum proportion of RE set at 60% and an optimization over one year. HOMER software is developed by National Renewable Energy Laboratory, is an optimization and simulation software widely used to study energy production [4], and to optimally size a hybrid system based on RE, taking into account both technical and economic aspects [13]. HOMER simulations are based on several input data, including available resources, technical and economic characteristics of components, constraints, load profiles, control and management strategies, and other essential parameters [20]. This process includes three steps: simulation, optimization, and sensitivity analysis. HOMER performs repeated hourly simulations and evaluates technological viability and life cycle costs during simulation. Then, during optimization, it recommends the optimal system that satisfies the requirements for technical and economic feasibility. Finally, sensitivity

analysis explores various conditions to assess model uncertainty [15], [21]. Figure 3 shows the study's methodological flow diagram, including the main functionalities [12]. Economic analysis focuses on financial parameters including total initial cost, total net present value, operating and maintenance costs, and energy cost [20].

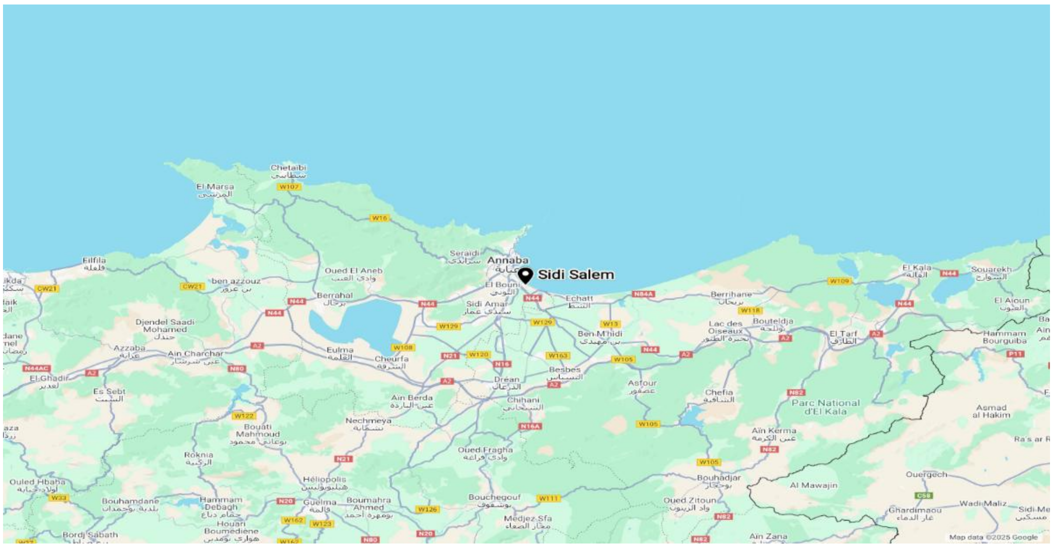


Figure 1. Site location

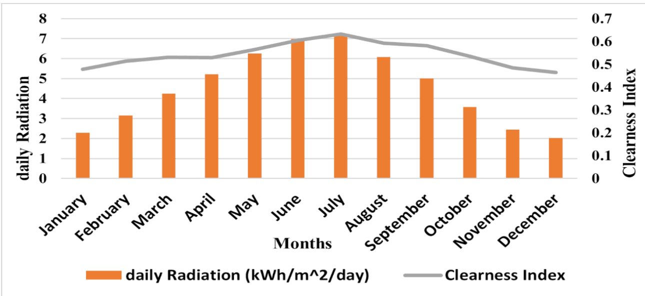


Figure 2. Variation in solar irradiance over the year

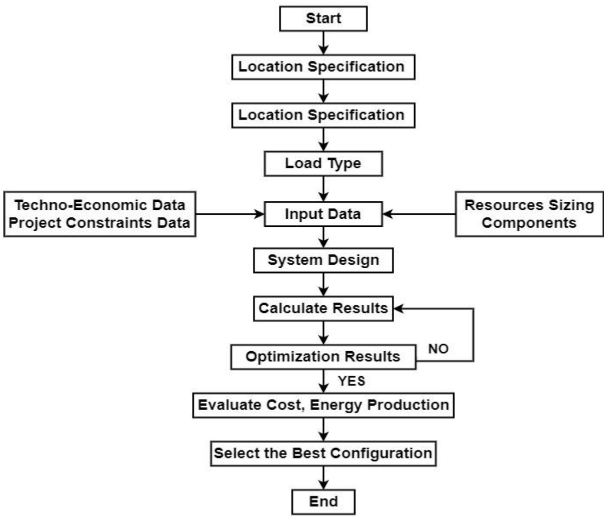


Figure 3. Research methodology

2.1. Net present cost

The net present cost (NPC) refers to the present worth of all costs associated with the system over its lifespan, less the value of the incomes earned during the venture's life expectancy. it is calculated using the following relationship [15], [22], [23]:

$$NPC = \frac{C_{an.Tot}}{CRF(i,t)} \tag{1}$$

$$CRF(r,t) = \frac{r(r+1)^t}{(r+1)^t-1} \tag{2}$$

where $C_{an.Tot}$ is absolute annual cost, CRF is a capital recovery factor, i is the real interest rate (%), and t is the project life time.

2.2. Cost of energy

The COE is defined as the average expenditure per kWh of useful electrical energy produced by the system, t is calculated according to the following relationship [2].

$$COE = \frac{C_{an}}{E_n} \tag{3}$$

E_n is the annual energy supplied tothe load (kWh), excluding exess energy.

3. FUEL CELL SYSTEM MODELLING

Hydrogen fuel cell system (FCS) has the ability to use hydrogen as an energy storage method. This type of system consists of three key components: FC, electrolyzer, and hydrogen storage tank. The electrolyzer generates hydrogen from sustainable energy sources. For this study, a 100 kW electrolyzer with an efficiency of 85% and an estimated lifetime of 25 years was selected. The initial, replacement, and the annual maintenance costs are set at 1,359.13 €/kW, 906.08 €/yr, and 18.12 €/yr respectively [21]. A generic 30 kW FC model, with an estimated lifetime of 50,000.00 hr was also used. The installation, replacement, and annual maintenance cost of the FC are 545.53 €/kW, 454.61 €/kW, and 0.073 €/op respectively [21]. And, a generic hydrogen tank with a capacity of 200 kg and lifespan of a 25 yr. The costs uf this tank are 1,087.30 €/kg, 724.87 €/kg, and 13.59 €/yr for installation, replacement and annual maintenance respectively [21].
The electrolysis process is expressed using the following relationship [24].

$$2H_2O \rightarrow 2H_2 + O_2 \tag{4}$$

FC represent an innovative and promising technology for exploiting hydrogen. They produce electricity through an electrochemical reaction between hydrogen and oxygen, without combustion, following a process opposite to that of electrolysis, this operation is successfully described by the equations for the anode, the cathode, and the overall reaction presented above [7]:

$$4H^+ + 4e^- \rightarrow 2H_2 \tag{5}$$

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{6}$$

$$2H_2O + 4H^+ + 4e^- \rightarrow 2H_2 + O_2 + 4H^+ + 4e^- \tag{7}$$

The hydrogen consumption of FC can be formulated through the following mathematical expression [25]:

$$N_{H_2} = \frac{I_{FC}}{2F} \tag{8}$$

or F is the internal capacitance of the FC, whereas, I_{FC} being the output current of FC stack.

4. DISPATCH CONTROL STRATEGY

Different control methods can be employed, such as a programmable logic controller and a microcontroller [2]. For this analysis, the load tracking (LF) strategy was used. This strategy is preferred because it effectively minimizes excess energy and total net present cost. Its primary purpose is to maintain and respond to AC load, prioritizing PV generators to meet load demand [8]. When there is excess PV energy, it is used to charge the batteries or to produce hydrogen via the electrolyzer [20]. If the PV energy is insufficient,

the system checks the state of charge (SOC) of the batteries to decide whether to use the FC or the DG. The FC is activated in configurations 3 and 4, to handle loads that the batteries cannot support. while the DG is used to fill the electricity gaps. In configurations 1 and 2, the energy needed to replenish the battery charge is provided by PV [21]. If the minimum power of the DG exceeds the power shortfall, it is engaged to fulfill the charging requirements, while the energy produced by the PV is utilized to recharge the battery bank.

5. RESULTS AND DISCUSSION

This part outlines the results of the performance, cost, and environmental impact analyses for all configurations. HOMER software was used for the simulation at 60-minute intervals. The analysis of input data was conducted and compiled into tables to assess the performance of hybrid systems incorporating FC. a summary comparing the various simulation outcome parameters for the all configurations is summarized in Table 1. The techno-economic analysis reveals that configuration 2 offers the best long-term financial attributes, Exhibiting the minimal COE and NPC. However, it causes the highest pollution due to diesel. In contrast, configuration 1 (PV/BAT) requires more batteries to eliminate emissions and eliminate the need for diesel, resulting in higher costs compared to PV/BAT/DG. and a greater surplus of electricity.

Table 1. Comparison of the performance across the configurations

Variable	Configuration 1 PV-BAT	Configuration 2 PV-BAT-DG	Configuration 3 PV-BAT-FC	Configuration 4 PV-BAT-DG-FC
Annual PV generation (kWh)	$99{,}1.10^3$	$66{,}7.\ 10^3$	$92{,}6.\ 10^3$	$66{,}8.\ 10^3$
Number of batteries	25	9	11	9
Annual DG generation (kWh)	-	$11{,}4.\ 10^3$	-	$9{,}4.\ 10^3$
Annual FC generation (kWh)	-	-	$2{,}7.\ 10^3$	$2.\ 10^3$
COE (€)	759.10^{-3}	358.10^{-3}	1.03	897.10^{-3}
NPC (€)	$5{,}92.10^5$	$2{,}79.10^5$	$8{,}02.10^5$	7.10^5
Annual OC (€)	$15{,}4.10^3$	$9{,}7.10^3$	14.10^3	$13{,}7.10^3$
INC (€)	$3{,}9.10^5$	$1{,}6.10^5$	$6{,}2.10^5$	$5{,}2.10^5$
Excess electricity (kWh/yr)	$33{,}7.10^3$ (34%)	$13{,}6.10^3$ (17.3%)	$13{,}1.10^3$ (13.8%)	$3{,}1.10^3$ (4.05%)
Unmet electric load (kWh/yr)	36,6 (0.0606%)	12.7 (0.021%)	15.5 (0.026%)	7.22 (0.012%)
Ren frac (%)	100	81.1	100	84.5
Battery autonomy (hr)	38.3	13.8	16.8	13.8
Annual CO_2 emission (kg)	0	11 693	**-0.176**	9 833

The addition of FC to the first two configurations aimed to reduce power losses, and CO_2 emissions, number of batteries while maintaining system dependability and stability, but their evaluation showed that hybrid storage system (HSS) combining batteries and hydrogen was not as profitable as the first configurations. However, technically, they managed the excess energy and deficit better as illustrated in Figure 4, reducing power losses by up to 60.98% in configuration 3 and 76.60% in configuration 4 compared to basic configurations, due to a larger availability of hydrogen storage capacity. and with increased hydrogen production capacity, these configurations also reduced the unmet power by up to 57.65% in configuration 3 and 43.15% in configuration 4. Additionally, the integration of FC reduced the number of batteries and the use of DGs, there by reducing CO_2 emissions in configuration 4 compared to configuration 2. Configuration 4 stands out as the most economical and technically viable, with the minimal NPC and COE. It uses a reduced number of batteries, experiences less electricity loss, and integrates more RE, according to Figure 5, highlighting its significant economic benefits.

The monthly electricity production in the selected configuration presented in Figure 6 shows a predominance of the PV generator, with 85.34% of the annual production, continuing with the DG at 12.07% and the FC at 2.57%. PV mainly powers the AC load (43.76%) and charges the batteries (40.77%), meanwhile, the electrolyzer uses the surplus to generate hydrogen (15.47%).

The energy balance of the hybrid configuration (PV/BAT/FC/DG) is discussed using an operational prototype 24 hours a day for 3 months, demonstrating that the PV generator predominates during the day, Furthermore, this maximum power of the PV is aligned with the charging process of the battery energy storage system (BESS) as well as the electrolyzer's input power, overnight the system uses the energy stored in the batteries to fill power gaps when the solar panels are not active as illustrated in Figure 7(a) (February 10 at 04 p.m), if the demand exceeds the capacity of the batteries, the DG or FC comes into play to provide the necessary electricity (February 8 from 05 p.m to midnight). The DG is activated only in case of power shortage with elevated power requirement, assisting the storage system in supplying the necessary power to meet the load demand, as illustrated in Figure 7(b) (the 10^{th} of July at 07 p.m and 09 p.m), and in cases where the storage capacity is inadequate. and when solar panels produce more energy than needed during the day, the excess is

stored in batteries. Once the batteries are full, the surplus is used to produce hydrogen through water electrolysis. This hydrogen is then stored for later use, which maintains the energy balance of the system through the LF control strategy.

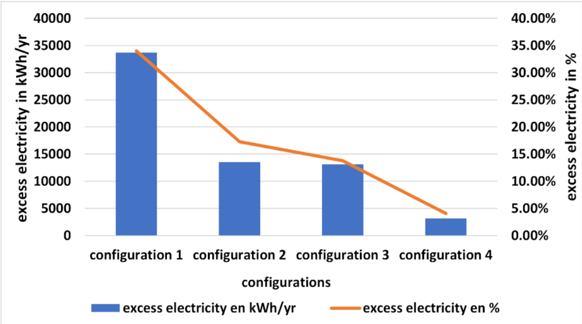


Figure 4. Surplus energy quantity across all configurations

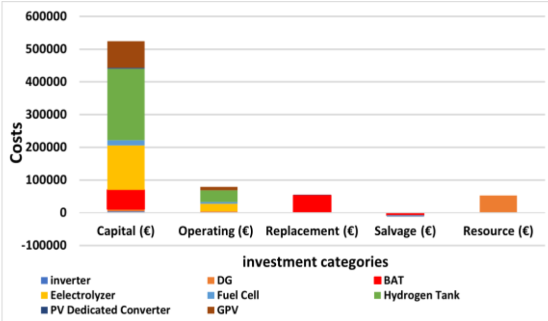


Figure 5. Total net present cost of the hybrid system components

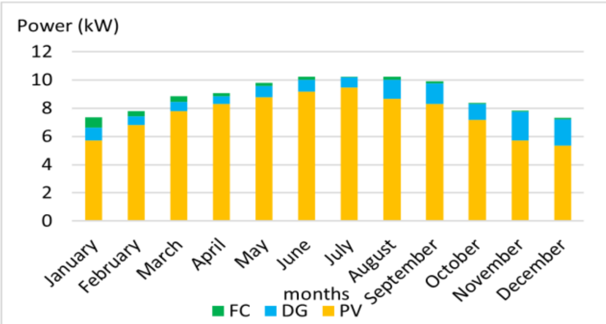
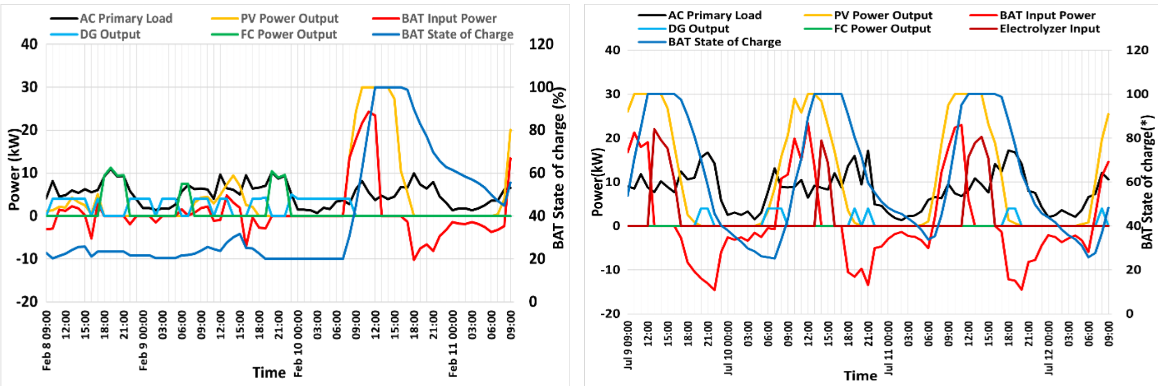


Figure 6. Monthly average electric production



(a) (b)

Figure 7. The different power outputs of the system components for; (a) February and (b) July

Figures 7 and 8 demonstrate the whole pile of piles of combustible hydrogen in the optimization of the continuation of the energy application over long periods. The stored hydrogen is utilized to produce electricity during peak energy demands, as shown in Figure 8, which reduces the waste of excess energy and helps alleviate energy shortages.

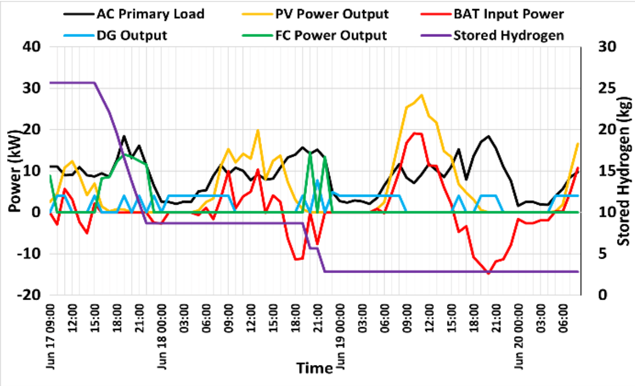
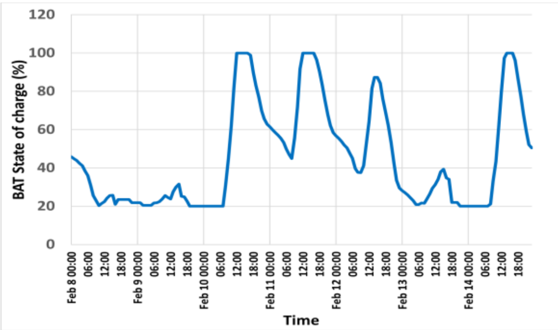
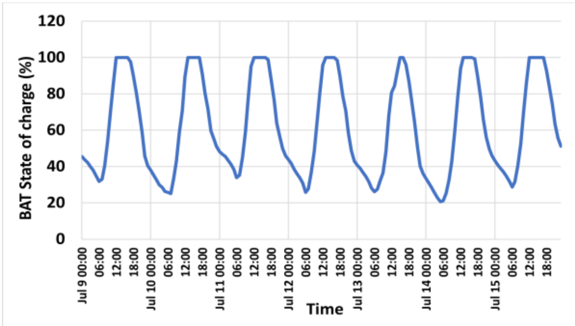


Figure 8. The different powers of the system components (June)

Batteries play a fundamental function in maintaining the system's stability, thereby improving its performance. SOC data for batteries in February and July is shown in Figures 9(a) and (b), demonstrating the importance of managing them to avoid overcharging. Without this system, a considerable surplus of energy could occur, but the integration of FC makes it possible to minimize this waste.



(a)



(b)

Figure 9. Battery charge status per hour for the studied configuration in; (a) February and (b) July

6. CONCLUSION

This study performed an in-depth comparative analysis of the technical and economic aspects of four hybrid system configurations, focusing on PV/BAT/FC and PV/BAT/DG/FC systems that incorporate FC, and comparing them to the simpler PV/BAT and PV/BAT/DG configurations. HOMER software evaluated these configurations according to technical, economic, and environmental criteria while proposing a global energy management strategy. This strategy aims to manage energy flows between the different sources to guarantee continuous yearly electricity production. The results demonstrate the crucial importance of integrating FC to improve the management of energy surpluses and reduce losses. In particular, configuration 4 (PV/BAT/FC/DG) stands out for its exceptional performance: a reduced energy excess of 4.05%, a minimal unmet load of 0.012%, a high renewable fraction of 84.5%, and significant economic benefits with an energy cost of 897.10^{-3} € and a net present cost of 7.10^{5} €. These results highlight the feasibility and reliability of this configuration and its potential to contribute to a sustainable energy transition by decreasing reliance on fossil fuels and minimizing environmental impact. Configuration 4 represents an important step forward for the development of autonomous and sustainable energy systems and paves the way for future research to optimize the performance of hybrid systems further.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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Nassim Bouzidi														

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The meteorological data used in this study were obtained from NASA's Surface Meteorology and Solar Energy database. The data were accessed through the HOMER software by specifying the study site.

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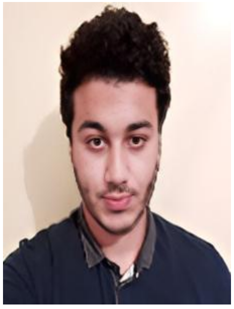

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